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ANALYSIS OF BAND PRESSURE IN A GUN TUBE USING FINITE ELEMENTS AND SHELL PUSHING DATA

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The five basic loads in an actual gun-projectiles system are the gas pressure, the band pressure, the frictional force, the angular torque and the body forces. The frictional force and the angular torque contribute little to the straining of the gun tube in the axial and tangential directions.[1] The strains due to the gas pressure, the band pressure and the axial acceleration are of substantial magnitude. The band pressure is of considerable interest since it is not only one of the dominant loads, but also one of the most difficult to determine.

Shell-pushing tests[2] and actual gun firings[3] are used to obtain the strain due to the band pressure. In shell-pushing studies, the gas pressure, the body forces and the torque are not present, consequently the strains measured are produced solely by the band pressure and the frictional force. In actual firings, all the loads are present. However, the effects of frictional force and torque are usually neglected.[3] In both types of tests the strain due to band pressure is the difference between the measured strain and strains caused by the other loads.

Band pressures have been previously calculated[1,2] from observed strains and from data published in the Watertown Arsenal Thick-Walled Cylinder Handbook.[4] In this handbook the gun tube is modeled as an infinitely long thick-walled cylinder having an effective wall ratio. In addition, similar idealized calculations are included in the handbook to determine the strains due to the other loads.

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In this report, effective band pressures are calculated from data obtained through shell-pushing experiments in conjunction with the finite element method of stress analysis for the two-independent variable cases. The finite element technique takes into account the irregular geometry of the gun tube. However, the effect of gun tube rifling and the missile groove are neglected. In addition, the band pressure and shear stress are assumed to be uniform.

METHOD OF ANALYSIS

In the shell pushing experiment, the strain gages located on the outer surface of the gun tube measure the response due to the rotating band and also the response due to the frictional force. The finite element method of stress analysis is used to reduce the shell-pushing data and calculate the pressure between rotating band and gun tube.

The frictional forces are included by assuming that the load required to push the shell is resisted by a uniform shear stress distributed over the surface of the rotating band. Knowing this stress and the response of the gun tube to a uniform shear stress, we can calculate the strain caused by the frictional force, and consequently obtain the strain produced by the band pressure alone. Assuming the band pressure is uniform, the band pressures can also be calculated if the response of the gun tube to a uniform normal pressure is known.

The two independent variable finite element method is used in the present work to calculate the response of the gun tube to an applied uniform normal stress and a uniform shear stress. This finite element code was revised and adapted to the BRLESC*.

The longitudinal cross-section of this tube is shown in Figure 1. The finite element representation for the gun tube is selected first. Because of the computer storage demands -- imposed by the size of the finite element grid required to model the entire tube -- the gun tube must be modeled one section at a time. Figure 1 also depicts a finite element representation for the breech section of the tube.

*Ballistic Research Laboratories Scientific Computer

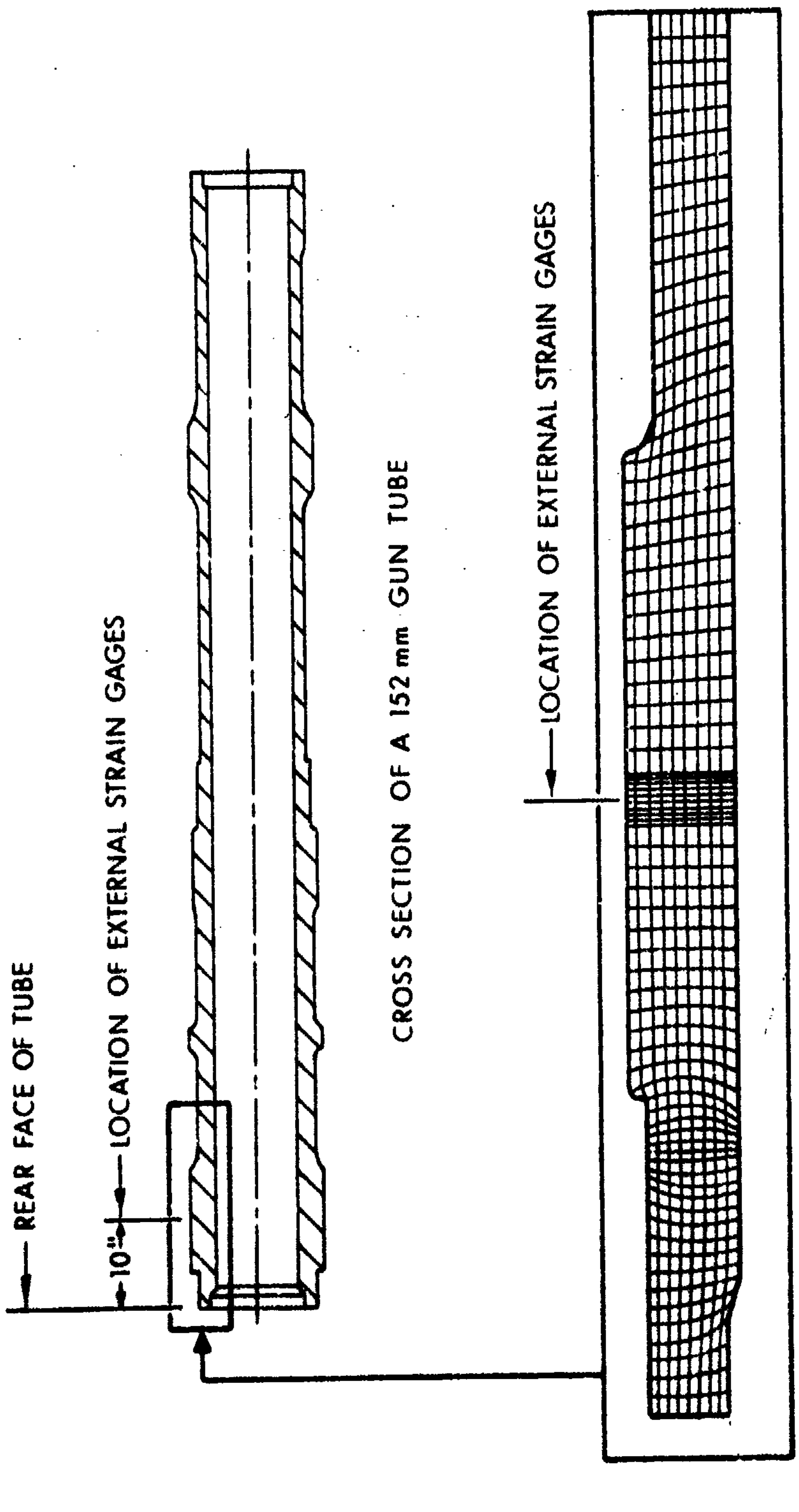

Figure 1. Finite Element Representation for the Breech Section of a 152 mm Gun Tube.

There are two basic reasons for the finite element arrangement shown in Figure 1. First, the stresses and strains are computed at the center of each element. Consequently, a fine mesh must be used in areas of high stress gradients to obtain an accurate picture of the actual stress distribution. Second, a uniform shear or normal stress can be applied on the side of a boundary element i.e. the inside diameter of the tube.

We are interested in calculating strains on the surface of the tube at selected strain gage locations when the rotating band centered at these positions. In the regions where strain gages are mounted, the elements are concentrated. To obtain strains on the surface of the tube, the known strains at the center of the elements must be extrapolated. To minimize these extrapolation errors, a row of elements whose centers lay along the same radial line as the strain gage is used.

Figure 2 is a portion of the finite element grid of Figure 1 where external tangential and axial strain gages are located on the surface of the tube. In Figure 2, A-B is equal in length to the width of the rotating band; the sides for all the elements along A-B are also equal in length. A column of elements is positioned so their centroids lay along the same vertical line, the distance from the rear face of the tube as the strain gages.

To calibrate the tube in this region a uniform normal pressure $\bar{P}_B$ is first applied along A-B and extrapolated to the surface the axial and tangential strains computed by finite elements of centroids 1 through 9 (see Figure 3). The strains obtained in this fashion are designated $\bar{\varepsilon}_{\theta B}$ and $\bar{\varepsilon}_{zB}$, tangential and axial strains, respectively, for a uniform band pressure $\bar{P}_B$. Similarly we find $\bar{\varepsilon}_{\theta S}$ and $\bar{\varepsilon}_{zB}$ for a uniform shear stress $\bar{\sigma}_s$ acting along A-B (see Figure 4).

Included in the shell-pushing data is a record of the force P_s required to push the shell at any axial location in the tube. P_s is found when the rotating band is positioned along A-B and assumed that it is balanced by a uniform shear stress σ_s acting along the inner tube wall. The shear stress is given by

$$\sigma_s = \frac{P_s}{2\pi\ r_o\ bw} \tag{1}$$

where b_w is the width of the rotating band and r_o is the inside radius to the grooves.

Having the axial and tangential strains, $\bar{\varepsilon}_{z_s}$ and $\bar{\varepsilon}_{\theta_s}$, respectively, for a uniform shear stress, $\bar{\sigma}_s$, the strains caused by the frictional force are computed by using

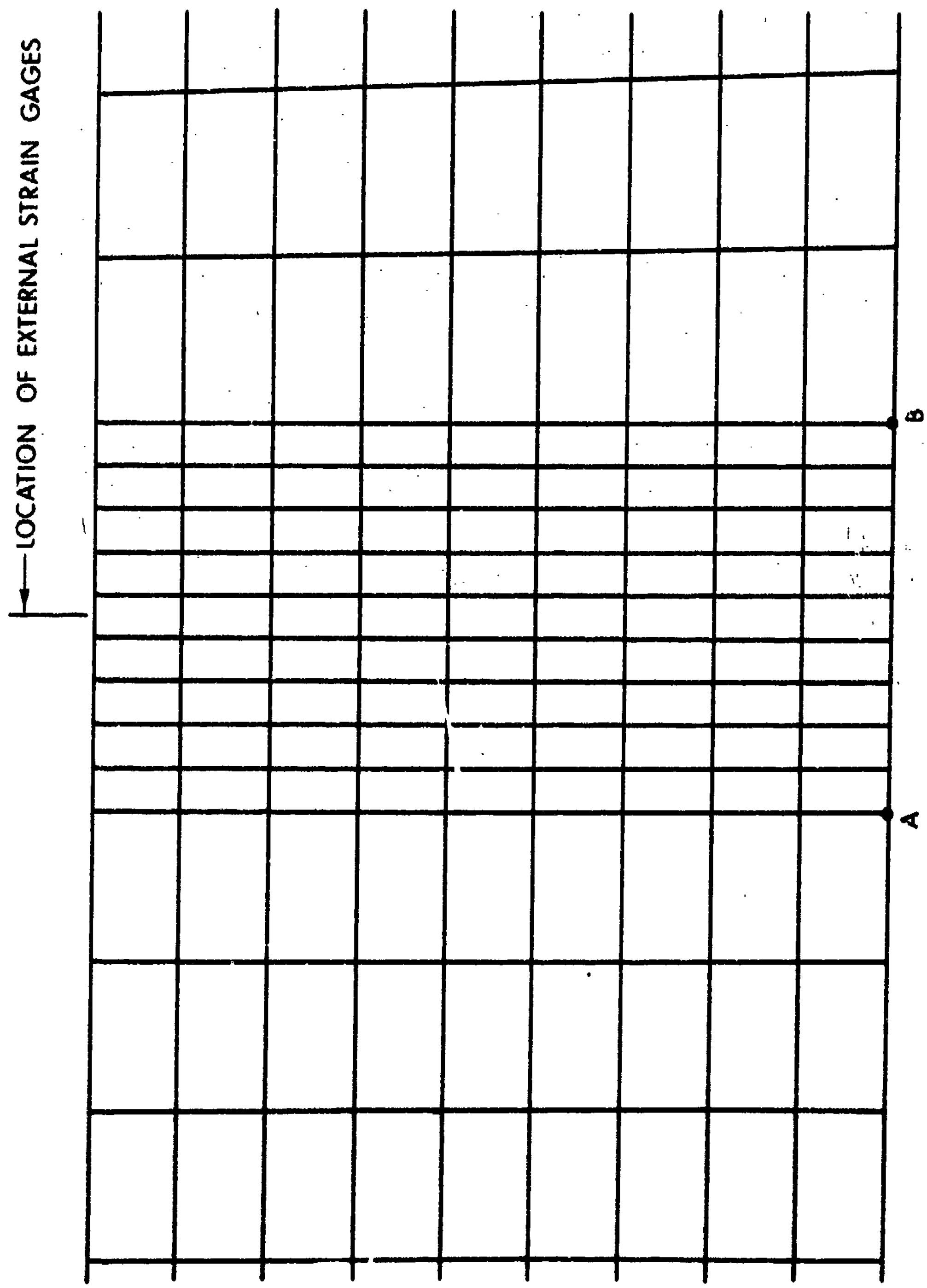

Figure 2. Enlarged Portion of Finite Element Grid Shown in Figure 1.

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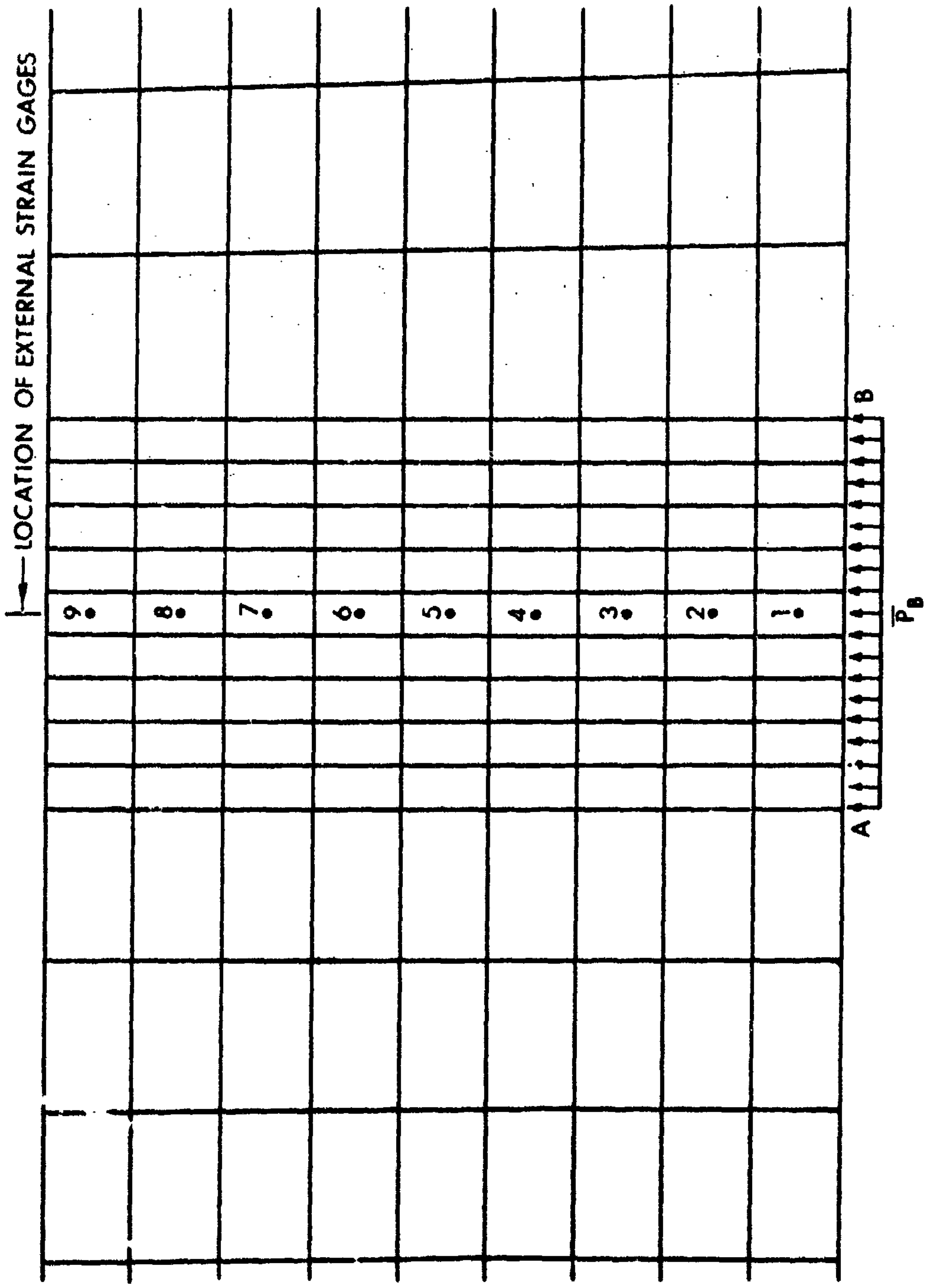

Figure 3. Application of Uniform Band Pressure $\overline{P}_B$ on 152 mm Gun Tube.

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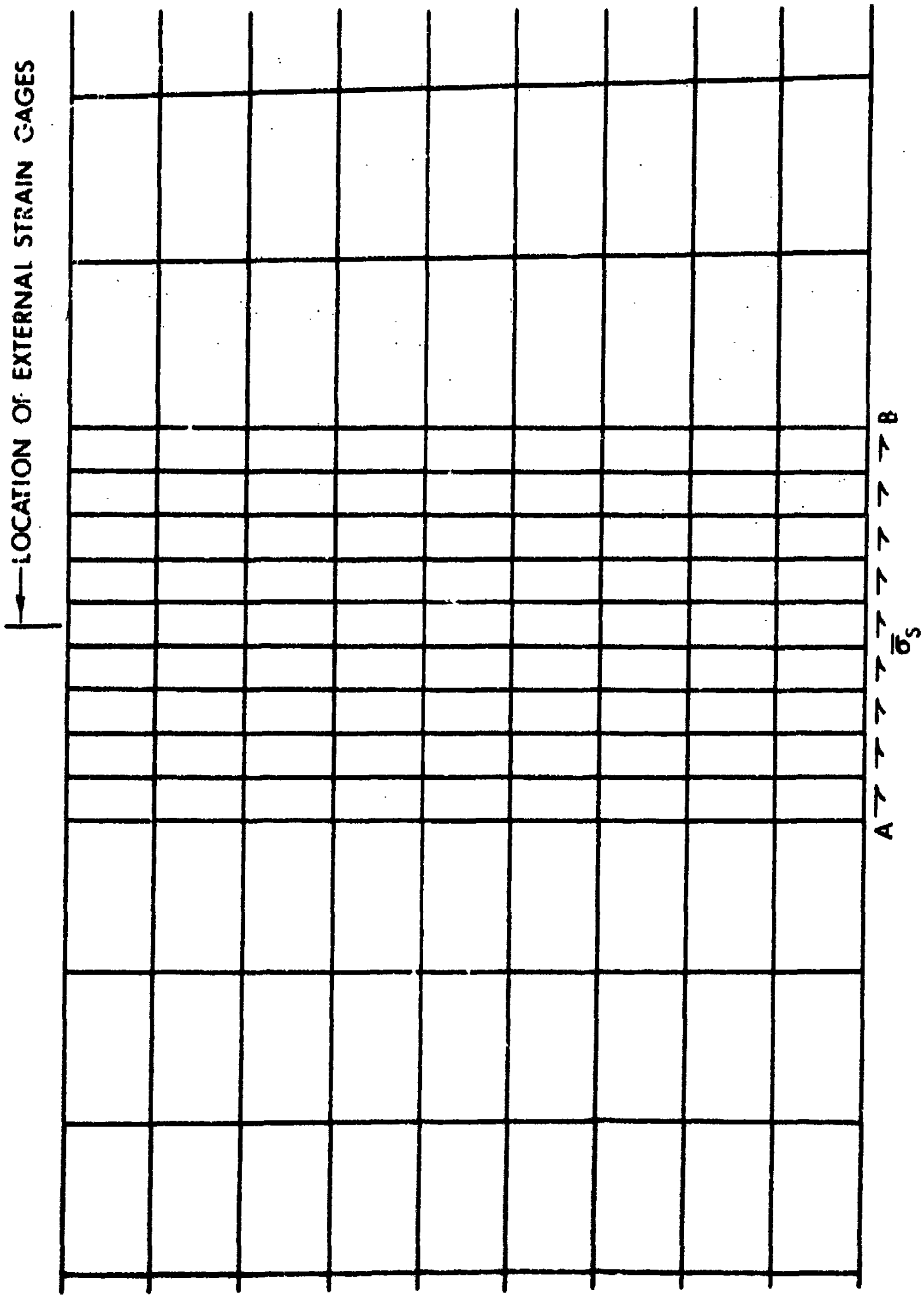

Figure 4. Application of Uniform Shear Stress $\overline{\sigma}_s$ on 152mm Gun Tube.

$$\varepsilon_{z_s} = \bar{\varepsilon}_{z_s} \frac{\sigma_s}{\bar{\sigma}_s} \tag{2}$$

$$\varepsilon_{\theta_s} = \bar{\varepsilon}_{\theta_s} \frac{\sigma_s}{\bar{\sigma}_s} \tag{3}$$

The strains, ε_{θ_T} and ε_{z_T}, which are recorded when the rotating band is positioned along A-B, are equal to the sum of the strains due to frictional force and band pressure. This is represented in equation form by

$$\varepsilon_{\theta_T} = \varepsilon_{\theta s} + \varepsilon_{\theta_B} \tag{4}$$

$$\varepsilon_{z_T} = \varepsilon_{z_s} + \varepsilon_{z_B} \tag{5}$$

Solving equations (4) and (5) for ε_{θ_B} and ε_{z_B}, respectively, gives

$$\varepsilon_{\theta_B} = \varepsilon_{\theta_T} - \varepsilon_{\theta_s} \tag{6}$$

$$\varepsilon_{z_B} = \varepsilon_{z_T} - \varepsilon_{z_s} \tag{7}$$

Having $\bar{\varepsilon}_{\theta_B}$, $\bar{\varepsilon}_{z_B}$, ε_{θ_B}, and ε_{z_B} the band pressure is calculated by

$$P_B = \bar{P}_B \frac{\varepsilon_{z_B}}{\bar{\varepsilon}_{z_B}} \tag{8}$$

$$P_B = \bar{P}_B \frac{\varepsilon_{\theta_B}}{\bar{\varepsilon}_{\theta_B}} \tag{9}$$

For the present work equation (9) is the more precise for two reasons. First, $\bar{\varepsilon}_{\theta_B}$ is more accurate than $\bar{\varepsilon}_{z_B}$ because the former strain is more accurately extrapolated from known strains. The radial variation of axial strain is more nonlinear as the outside surface of the tube is approached.

The second reason equation (9) is more reliable than equation (8) is that $\varepsilon_{\theta B}$ is less dependent upon the frictional force than ε_{zB}. Consequently the assumption of uniform shear stress does not play as decisive a role in computation of the tangential strain as it does in calculation of the axial strain.

The use of equations (8) and (9) provides a check on our computation of band pressure. The same approximate P_B should be obtained by using both formulae. However, another check on our band pressure calculations has been incorporated by modifying an XM409 shell and placing a tangential strain gage on the inside beneath the rotating band, and pushing it through the tube. This gives a record of tangential strain in the shell at any axial location in the tube.

This modified shell is analyzed for tangential strain caused by uniform shear and normal pressures in the same manner as the gun tube. Figure 5 is a finite element representation for the shell. Using equation (9) the band pressure is calculated at any desired location in the gun tube. We can compare the band pressures computed using the shell with those calculated using the gun tube when the shell is appropriately positioned beneath a strain gage position.

TEST PROCEDURE

A 152mm M81 autofrettaged gun tube was instrumented for strain data acquisition. Electrical resistance type strain gages were used to measure the strains on the outer surface of the gun tube. Sets of strain gages were attached 180° apart axially and tangentially at eight locations on the outer surface of the gun tube.

Three types of 152mm projectiles were used for the shell pushing tests. Table I shows the type and characteristics of each projectile.

TABLE I. 152MM PROJECTILES

PROJECTILE	ROTATING BAND	FUZE BASE PLUG
XM409E4 HEAT-MP-T	Sintered Iron	Steel-Removable
XM411E3 HE-TP-T	Sintered Iron	Aluminum-Removable
XM657E2 HE-T	Gilding Metal	Steel-Not Removable

The base of all projectiles was modified. Modification of the base was necessary to increase the bearing surface for the high axial loads expected. In addition, a XM409 body was further modified in the fuze well for application of strain gages.

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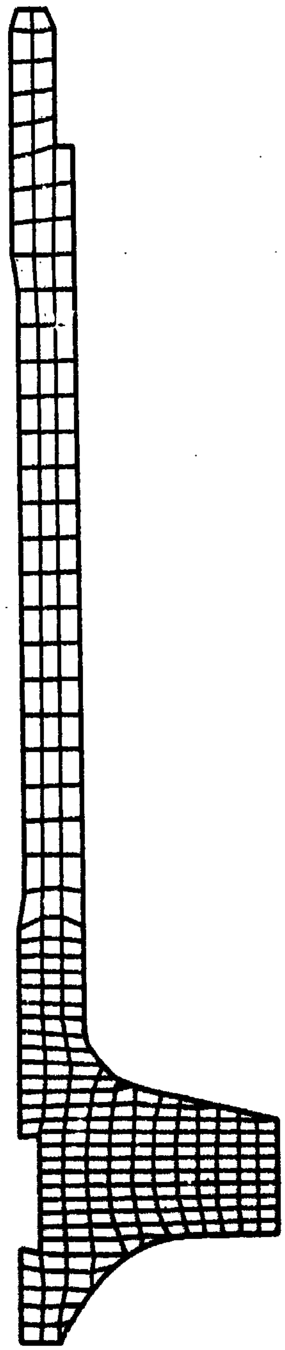

Figure 5. Finite Element Representation of Modified XM 409E4 Shell.

A Baldwin-Southwark 600,000 pound hydraulic universal test machine, with a power stroke of ten inches was used to push the projectile through the gun tube.

The shell pushing studies are divided into two phases. In the first phase, each shell was pushed through the tube twice in order to obtain an estimate of the work required to engrave the shell. The shells were indexed, so that a groove engraved on the rotating band during the first run would engage the same land during the second run. Each projectile was pushed through the tube only once during the second phase of the tests. The primary concern of these tests was the effect of different fuze plugs. These plugs affect the radial stiffness of the projectile. Ten strokes were required to push the projectile completely through the tube. In addition, molykote was applied to the origin of rifling area before each projectile was pushed.

A new "Data Logger" recorded all strains and the axial displacement of the projectile. This unit scans the analog signal sources sequentially; converts the data to four digit decimal form and records the data on magnetic tape.

RESULTS

The band pressures are calculated from the measured tube strains by the analysis outlined previously. The results for both phases of the experiment are given in Tables II and III respectively.

TABLE II. BAND PRESSURE CALCULATED FROM TUBE STRAINS

PHASE I

RUN	PROJECTILE	Pressure, psi x 10^{-3} STRAIN GAGE LOCATION					
		1	2	3	4	5	6
1	XM409E4	50	48	45	37	33	31
1A	XM409E4	27	35	30	26	23	22
2	XM411E3	53	47	34	28	23	22
2A	XM411E3	28	20	14	10	9.3	8.7
3	XM409E4	LOST	LOST	43	35	LOST	LOST
3A	XM409E4	26	32	28	27	23	21

Runs 1, 2, 3 prior to engraving
Runds 1A, 2A, 3A after engraving

TABLE III. BAND PRESSURE CALCULATED FROM TUBE STRAINS

PHASE II

RUN	PROJECTILE	Pressure, psi x 10^{-3} STRAIN GAGE LOCATION 1	2	3	4	5	6	7	8
1	XM657E3	53	59	49	45	39	37	25	24
2	XM657E3	55	60	52	45	40	39	25	25
3	XM411E3	57	61	54	41	38	39	25	25
4	XM411E3	56	53	50	39	35	34	21	21
5	XM409E4	48	49	44	35	31	LOST	22	22
6	XM409E4	51	53	44	35	LOST	LOST	17	17
7	XM409E4	43	48	40	31	27	24	16	16

The calculated band pressures were compared to the gas pressure-travel design curve for a 152mm gun tube. Near the breech, the band pressure is in the neighborhood of one and one-half times greater than the design gas pressure. However, near the muzzle the band pressure approaches a value four times the gas pressure.

The band pressure was also calculated from the response of the strain gage in the fuze cavity. The estimated band pressures were noticably lower than the band pressures calculated from the tube strains. Since the loading conditions were somewhat uncertain, a second calculation was made in which it was assumed that the base of the shell was laterally restrained. The agreement in band pressure calculated by the two methods was improved, but cannot be regarded as entirely satisfactory. The results are tabulated in Table IV.

TABLE IV. BAND PRESSURE CALCULATED FROM STRAIN IN FUZE CAVITY

CONDITION	Pressure, psi x 10^{-3} STRAIN GAGE LOCATION 1	2	3	4	5	6
Unrestrained base	38	39	30	25	22	21
Restrained base	41	44	33	27	24	23

Additional stress analysis of the shell showed that the tangential strain varied considerably over the width of the fuze cavity, so it was difficult to calculate the response of the strain gage with the desired accuracy. Morevover, the tangential strain was considerably affected by shear stresses, and other lateral constraints on the base of the shell. It is believed that these reasons are sufficient to account for differences between the rotating band pressure measured from the shell. The tube strains are considered more reliable measures of band pressure.

The force to engrave the projectile varied from 85,000 pounds to a maximum of 133,000 pounds for new projectiles. This variance in load is dependent in part on the interference fit between gun tube and projectile and to a lesser extent on the influence of the fuze base plug. Less work is required to push the pre-engraved projectiles through the tube, as expected. These results are consistent with the work of Herzfeld.[6]

CONCLUSIONS

The analysis of band pressure in a gun tube using finite elements and shell push data is of importantce in obtaining design data on gun tubes and projectiles. The methods developed in this investigation were used to analyze strains accurately even when the outside diameter of the tube was not constant i.e. the finite element method takes into account irregular geometries of the tube. Shell pushing has the advantage over firing tests in that they are less costly and are not subjected to many uncontrollable variables. In addition, corresponding projectile strain gage data can be obtained with exterior tube strain data.

The calculations of band pressure in the 152mm gun tube have shown that these pressures were greatly in excess of the design pressure in the thin portion of the tube. The 152mm projectiles have a solid web under the band, so they are much stiffer radially under the band than standard HE shells, which are generally hollow. In HE shells, the projectile wall under the rotating band yields locally and increases progressively as more force is applied. The magnitude of the band pressure increases in proportion to the elastic component of strain in the projectile; this component increases as yielding progresses.

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